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3400–Forest Pest
August 1991
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Wind Flow Models For Spray Transport In Complex Terrain

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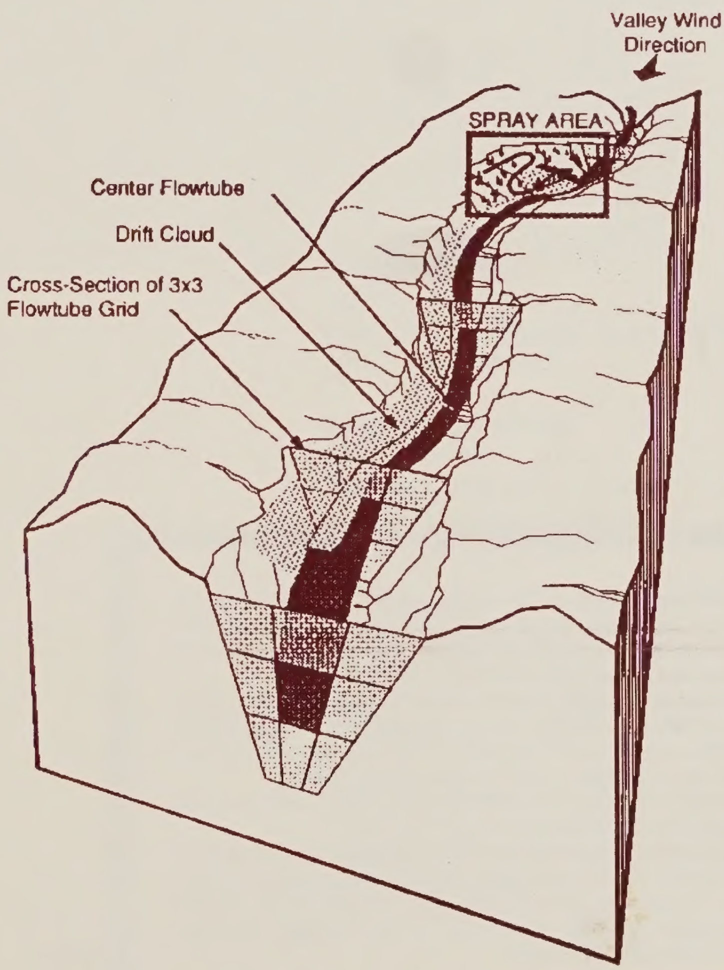

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Pesticides used improperly can be injurious to human beings, animals, and plants. Follow the directions and heed all precautions on labels. Store pesticides in original containers under lock and key—out of the reach of children and animals—and away from food and feed.

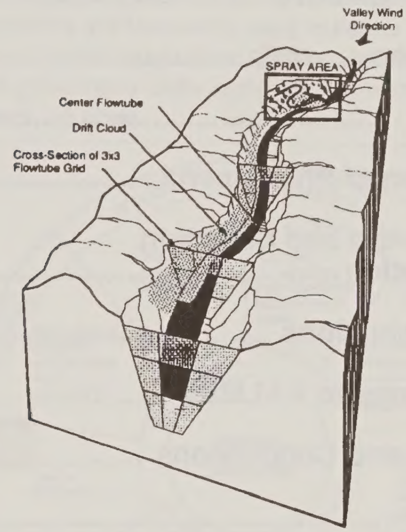
Apply pesticides so that they do not endanger humans, livestock, crops, beneficial insects, fish, and wildlife. Do not apply pesticides where there is danger of drift when honey bees or other pollinating insects are visiting plants, or in ways that may contaminate water or leave illegal residues.

Avoid prolonged inhalation of pesticide sprays or dusts; wear protective clothing and equipment, if specified on the label.

If your hands become contaminated with a pesticide, do not eat or drink until you have washed. In case a pesticide is swallowed or gets in the eyes, follow the first aid treatment given on the label, and get prompt medical attention. If a pesticide is spilled on your skin or clothing, remove clothing immediately and wash skin thoroughly.

NOTE: Some States have restrictions on the use of certain pesticides. Check your State and local regulations. Also, because registrations of pesticides are under constant review by the U.S Environmental Protection Agency, consult your local forest pathologist, county agriculture agent, or State extension specialist to be sure the intended use is still registered.

Wind Flow Models For Spray Transport In Complex Terrain



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5E52P29
Wind

August 1991

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Acknowledgment

Two of the authors, C. David Whiteman and K.J. Allwine at Pacific Northwest Laboratory, wish to acknowledge support from the USDA Forest Service under a Related Services Agreement with the U.S. Department of Energy (DOE) under Contract DE-AC06-76RL0 1830, Interagency Agreement 5E52P29. Pacific Northwest Laboratory is operated for DOE by Battelle Memorial Institute.

Introduction

This report documents the selection and adaptation of a computer-based model for predicting drift from aerially applied sprays in mountainous terrain. The model will be an addition to the AGDISP (Bilanin, et al, 1989) and FSCBG (Rafferty and Bowers, 1989) models that have already been adopted to describe spray dispersion and deposition in flat or uniform sloping terrain.

The inputs to the flat terrain models (meteorology, aircraft, nozzles, spray material and canopy) are constants and the algorithms predict the temporal and spatial changes based on the interaction of the constants and physical principles. The winds that move small airborne particles in flat terrain near the ground are generally caused by large-scale regional pressure differences that change on daily or hourly scales, and thus may be assumed constant for the brief aerial spray event. In mountainous terrain, strong local circulations, thermally driven by different rates of heating and cooling between valleys and surroundings, change in minutes. Assuming constant winds in these situations may lead to significant errors and neglect benefits of controlling drift based on predictable changes in local winds.

Methods

An interdisciplinary team of biological and physical scientists and engineers are frequently used to define and solve problems in aerial application (Ekblad, 1979). A wheel illustrating the many skills and discipline is shown in figure 1 (Matthews, no date).

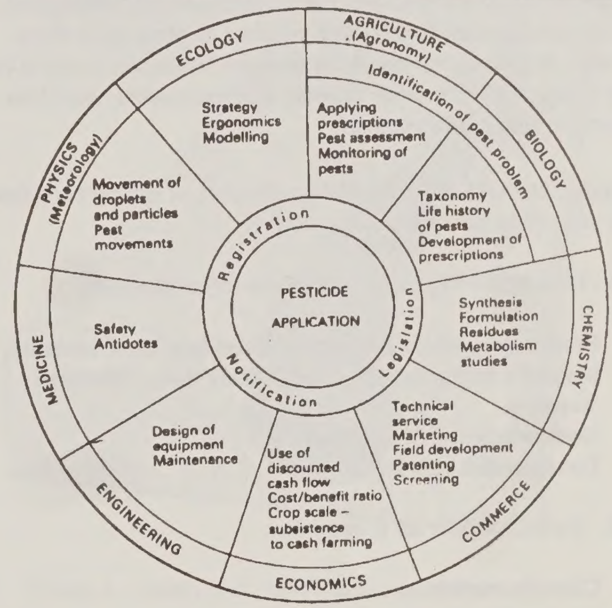

Figure 1.—Multidisciplinary nature of pesticide application.

The initial team members were selected to reflect this diversity:

Robert B. Ekblad Program Leader, MTDC, USDA Forest Service, Missoula, MT

Dr. Robert Meroney Professor, Fluid Mechanics and Wind Engineering, Colorado State University, Ft. Collins, CO

Dr. Milton Teske Senior Staff Engineer, Continuum Dynamics, Inc.,Princeton, NJ

Dr. C. David Whiteman Staff Scientist, Pacific Northwest Laboratory, Battelle Memorial Institute, Richland, WA

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In addition to the original members, many others have been advisors and contributors.

The objective was to select an existing complex terrain wind flow model and incorporate it into the AGDISP and FSCBG aerial spray models. The work was planned in three phases: Phase I, Model Selection and Evaluation; Phase II, Model Testing and Validation; Phase III, Model Merger and Technology Transfer. The plan was selected to provide a logical break in development at the end of each phase, and to allow managers to revise program direction and funding. It also provided for a complete product at the end of each phase. At the end of the three phases the product would be fully integrated with other models and specialists would be trained in use of the models.

Phase I, Model Selection and Evaluation, is nearly complete. It is described in the following outline:

A. Describe Physical Phenomena to be Modeled:

Prepare report on convective boundary layer breakup.
Measure turbulence in a local study area. Review literature.
Convene panel of advisors.
Develop drift scenarios.

B. Select Models for Evaluation:

Classify models.
Review literature.
Compare each class of model to requirements.
Establish criteria for drift model.
Recommend models for evaluation.

C. Determine Availability of Input Variables:

Review GIS systems.
Review digital terrain data bases.
Develop simplifying assumptions for source strength.
Develop meteorological, source, and terrain inputs.

D. Evaluate Selected Models:

Install selected models on local computers.
Review literature for drift data.
Compare model results to existing drift data.
Evaluate merging of complex terrain models to AGDISP and FSCGBGF.
Train other users.
Modify models as required.
Evaluate initial selection of models.

Description of Phenomena

As part of this project a report (Whiteman, 1990) was prepared describing the physical processes involved in mountain valleys during typical spray weather, with recommendations for forest spraying. Some highlights of the physical processes are reproduced here. The report describes conditions when upper winds are weak and weather conditions are undisturbed by large scale travelling storm systems such that circulations within the valley are entirely locally produced. Figure 2 illustrates the five interrelated wind systems during such a period, which is also typical, acceptable weather for spraying. Figure 3 illustrates the sequences in the early morning inversion destruction. In the center of the diagram are cross sections shown at times t_i, t_2, t_3, t_4, and t_D. On the left are the corresponding

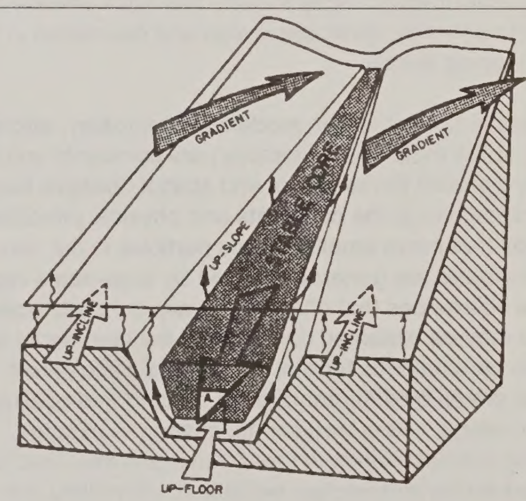

Figure 2.—Typical mid-morning wind structure over and within a deep valley on the western slope of the Rockies, illustrating the five interrelated wind systems.

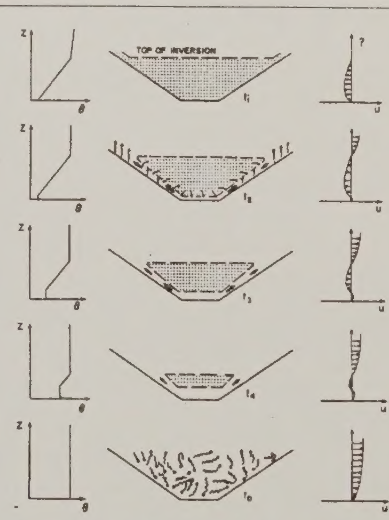

Figure 3.—Illustration of the hypothesis of inversion destruction.

temperature profiles at the valley center. On the right are corresponding up-valley wind components as a function of height. At sunrise, t_1, an inversion is present in the valley. At t_2, after sunlight has illuminated the valley floor and slopes, a growing convective boundary layer (CBL) is present over the valley surfaces. Mass and heat are entrained into the CBL from the stable core and carried up the sidewalls in the upslope flows. This results in sinking of the stable core and growth of the CBL (t_3 and t_4) until the inversion is broken (t_D) and a turbulent, well-mixed neutral atmosphere prevails in the valley. Whiteman observes, "Temperature structure evolution during clear, undisturbed weather was surprisingly uniform from day to day and from season to season. Thus, in pesticide spraying work, one may be fairly confident of observing typical inversion breakup in a pre-spray campaign data collection program in undisturbed weather. Despite variability in the strength and timing of reversal of winds, the temperature structure evolves uniformly from day to day in individual valleys."

Whiteman recommends, "Present understanding of valley meteorology during the morning transition period has progressed to the point where some useful planning tools could be constructed to optimize a forest spraying campaign." Inversion breakup models and simple air pollution dispersion models could be modified for support of forest spraying.

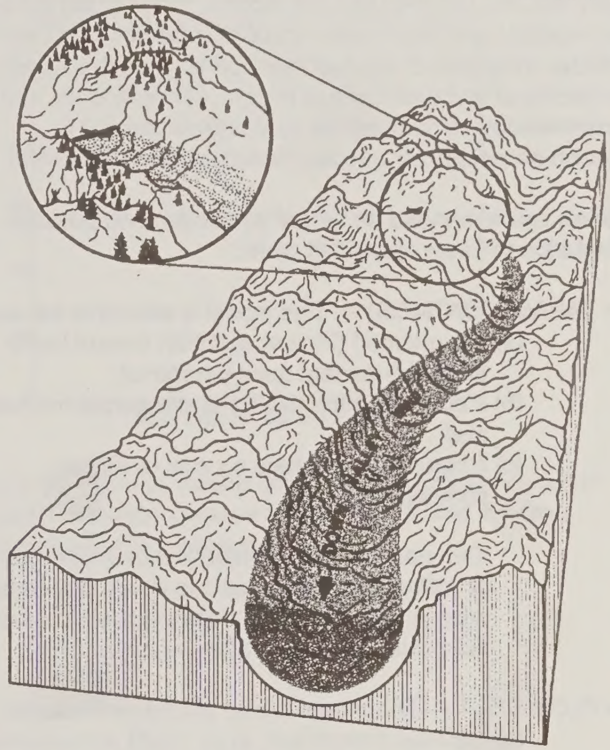

Figure 4.—Valley drift. Drift is contained in the valley.

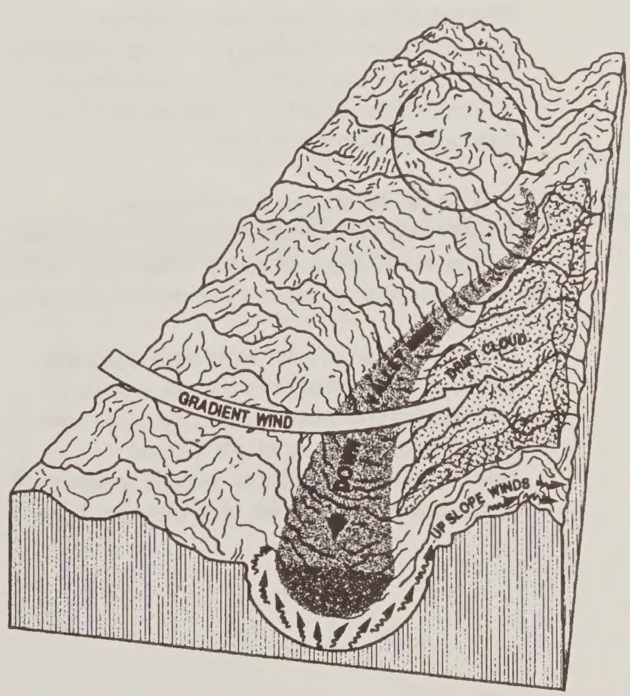

Figure 5.—Regional drift. The convective boundary layer carries drift out of the valley and into the regional winds.

Model Review and Selection for Evaluation

Even a cursory search reveals that hundreds of mesoscale, complex terrain meteorological models have been devised. Some scheme was needed to screen and evaluate models to ensure that the most appropriate state-of-the-art models were examined for inclusion in this development. The following sideboards were established: Models for consideration would be limited to operational (as opposed to research) models that have documentation available. Models would be limited to those using a similar order of magnitude of computer resources as current versions of AGDISP and FSCGB.

A classification for complex terrain meteorological models would be established and initial screening would be made by analyzing the advantages and disadvantages of each class of model. A differentiation was made between valley drift and regional drift. These two concepts are illustrated in figures 4 and 5. Efforts would be focused on valley drift. Dr. Robert Meroney, Professor of Fluid Mechanics and Wind Engineering at Colorado State University, undertook the task of classifying and reviewing models. His work is presented in "Review and Classification of Complex Terrain Models for Use with Integrated Pest Management Program Spray Model " (Meroney, 1990). His review includes an examination of the relative merits of Gaussian plume models, hill intercept models, phenomenological models, mass consis-

tency models, depth-integrated models, linear or perturbation models, and full primitive equation models. The review includes examples of appropriate models in each category, availability of a source code, a critique of the models, and recommendations concerning model development or revision necessary for use as a forest aerial spray model.

Models recommended for further evaluation and possible adaptation to forest spray drift were:

- TAPAS (NUATMOS) — This model is attractive because:
  (a) it is oriented (Fox, et al, 1986) toward forest and land-management personnel;
  (b) it contains attractive input and output module; and
  (c) it can operate quickly on mini or micro computers.

  The model should predict flow over undulating or rolling terrain in situations where drainage movements are small, ridge separation does not occur, and winds are moderate or high.

- FLOWSTAR — This model is also attractive because:
  (a) it is fully (Carruthers, et al, 1990) documented;
  (b) input and output modules could be modified to fit Forest Service needs; and (c) it can operate on mini-or micro-computers.

  The model can provide almost infinite resolution over undulating or rolling terrain in situations where drainage movements are absent, ridge separation does not occur, and winds are moderate or high.

- VALMET — This model is attractive because:
  (a) it inherently (Whiteman and Allwine,handles temporal variations of valley flows: and 1985)
  (b) it can operate on mini-size computer systems.

  The model can predict night-time and early-morning flow behavior in narrow valleys of simple platform where strong synoptic flows are absent. The model will require development before it can include intermittent flows, cross-valley flows, and tributary flows.

Model Evaluations

The TAPAS model is classified as a mass consistent model, FLOWSTAR is a linear or perturbution model, and VALMET is classified as a phenomenological model. System managers for both FLOWSTAR and TAPAS recommended against using their models because of limitations in following steep terrain.

Nevertheless, TAPAS was installed on the USDA Forest Service Data General MV 20000 in Missoula, Montana, to develop a feel for the use of a mass consistent model. Initially a terrain data field was generated from 7.5 minutes USGS data available on a mainframe computer owned by the USDA. These data were imported into the Data General and a wind field was generated using TAPAS. Finally, the dispersion cloud was introduced via a PUFF model and concentration contour maps were generated.

As predicted, the model would not follow the terrain contours generated using terrain data from a spray project conducted in 1979 in the Helena National Forest in Montana. However, it did appear that TAPAS would be operational for a regional drift model as defined earlier in this paper. Details of this model are given by Thompson (1991).

VALMET — a valley air pollution model (Whiteman and Allwine 1985) was developed to describe the dispersion of a constant down valley pollutant plume during the early morning solar driven breakup of the local inversion layer. VALMET allows 27 values of input parameters, most of which have default values. The solar heating is continuously calculated based on computations made using longitude, latitude, month, day, and time. The model was intended to simulate the effects on pollutant transport and diffusion of various meteorological processes that are thought to result in the worst-case pollutant concentrations. The model is run for situations where pollutants are carried in locally developed circulations within a valley when these circulations are "decoupled" from prevailing circulations above the valley.

While VALMET includes a variety of meteorological processes, it is highly parameterized so that it is simple in concept and easy to run. The model is composed of 13 modules, or subroutines, arranged in such a way that an improved understanding of individual valley meteorological phenomena can be easily incorporated in future versions of the model.

VALMET was installed on a personal computer for preliminary evaluation (Teske, 1990). The AGDISP (MOD 5.3) enhancements and plotting package were included to provide a user-interface that makes set-up, execution, and interpretation of VALMET results easier. Figures 6a through 6h are VALPLT outputs available directly from the personal computer version of VALMET. These outputs, for the

reference simulation of Whiteman and Allwine (1985) are for an elevated continuous plume carried down the axis of a valley. The nocturnal plume centerline at a 10 km distance down-valley from the plume source is at an elevation of 250 m AGL. Vertical and cross valley concentration profiles through the nocturnal plume centerline are shown in figures 6a and 6b and concentration isopleths on the valley cross section are shown in figure 6c. Following sunrise, a convective boundary layer grows upward from the valley floor and the temperature inversion top descends into the valley as shown in figure 6g. Because of fumigation, subsidence, and advection in the upslope flows, pollutant concentrations vary with time at grid elements thatlocated on the cross section at various positions on the valley floor and sidewalls (designated in figure 6f). The time-varying concentrations are shown for designated grid elements in figure 6d and, as a function of cross-valley distance, at selected times in figure 6e. Concentration contours are shown on a time-grid element (or time-cross valley distance) plot in figure 6f.

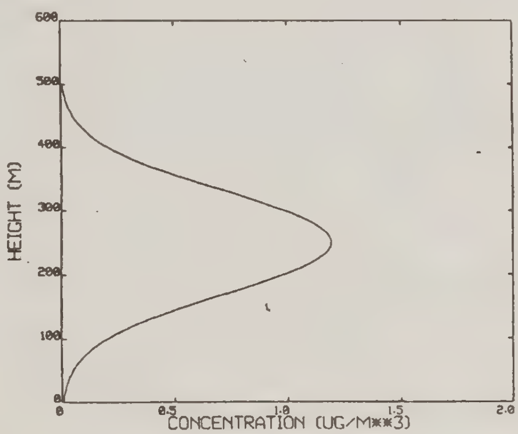

Figure 6a.—VALPLT outputs from personal computer version of VALMET: Vertical Gaussian Profile.

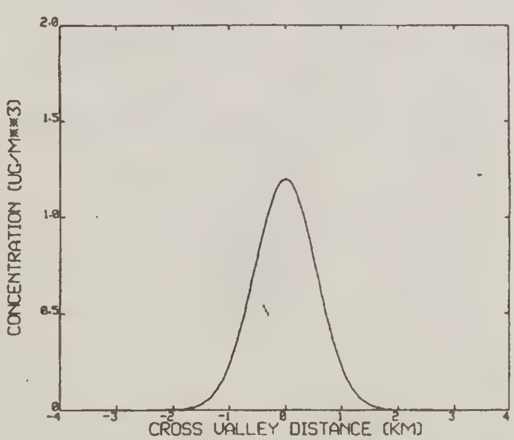

Figure 6b.—VALPLT outputs from personal computer version of VALMET: Cross Valley Gaussian Profile.

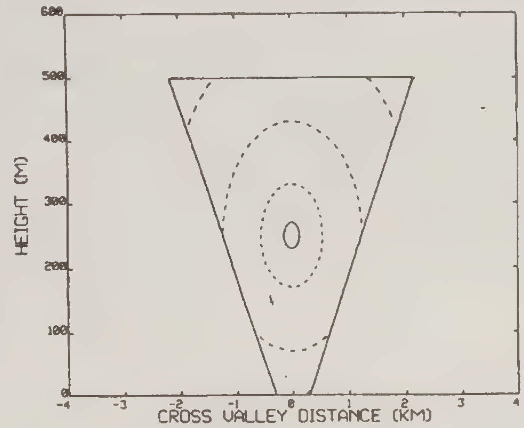

Figure 6c.—VALPLT outputs from personal computer version of VALMET: Gaussian Contours for 0.5, 1.0, 1.5, and 2.0 times standard deviation for plume.

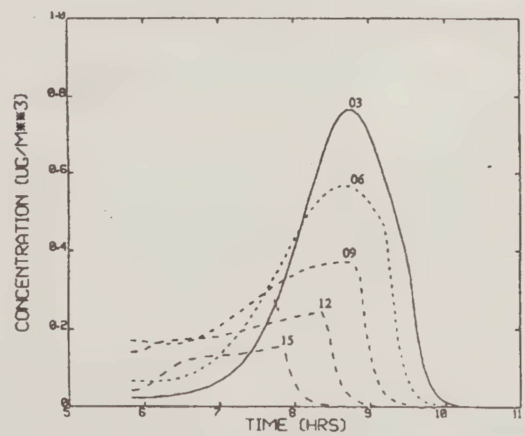

Figure 6d.—VALPLT outputs from personal computer version of VALMET: Concentration Time Histories.

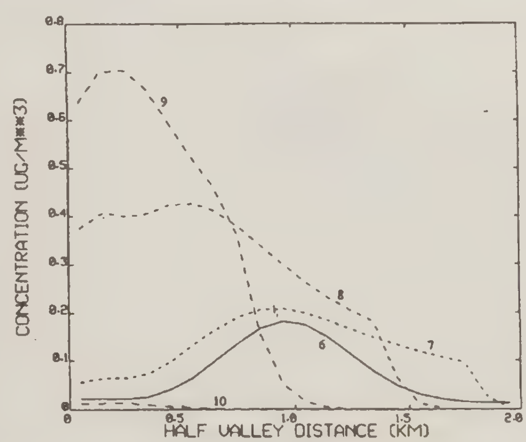

Figure 6e.—VALPLT outputs from personal computer version of VALMET: Cross valley concentrations with time.

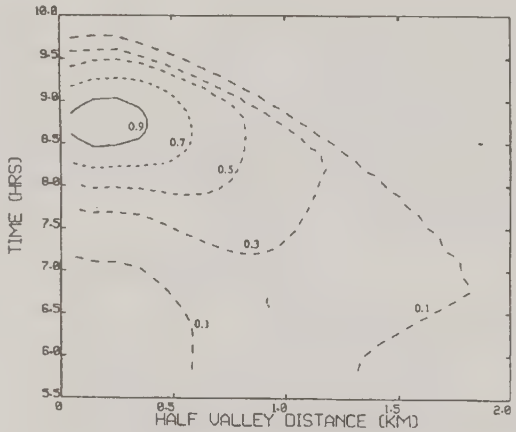

Figure 6f.—VALPLT outputs from personal computer version of VALMET: Concentration contours.

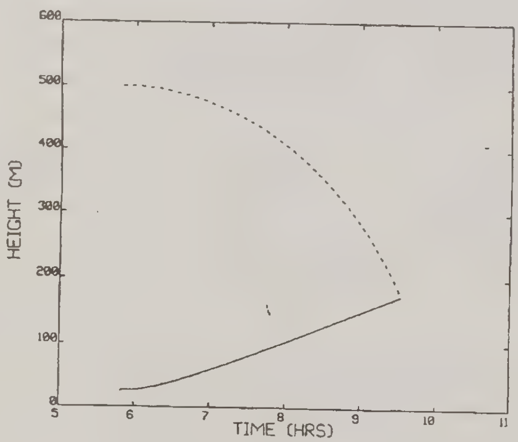

Figure 6g.—VALPLT outputs from personal computer version of VALMET: Inversion Heights (Lower curve is the growing convective boundary layer; the upper curve is the collapsing inversion height).

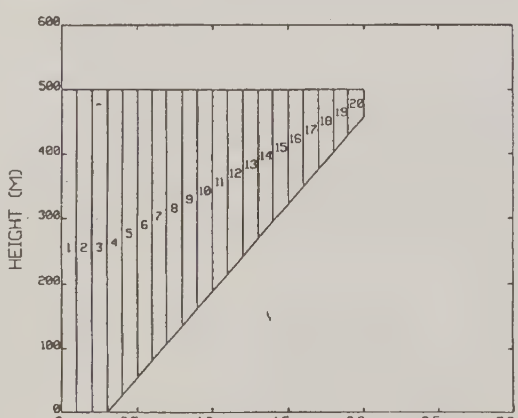

Figure 6h.—VALPLT outputs from personal computer version of VALMET: Cross valley solution elements.

Shortcomings of VALMET for aerial spray dispersion predictions were identified as:

- Down valley pollutant plume was continuous and frozen in time.
- Down valley winds could not be varied.
- A complete range of source/sink inputs were not incorporated in VALMET.

Modifications were proposed to alleviate these shortcomings, and the VALMET model was selected as the initial modeling tool for assessment of valley drift from aerial spraying operations. A brief description of the existing VALMET model and the planned modifications follows.

Modifications to VALMET

The VALMET model was originally developed for estimating ground-level concentrations from a continuous point source located in a valley. The model treats the down-valley transport of a continuous plume through the nighttime in steady winds, and the subsequent fumigation of the elevated plume to the surface during the morning transition period. The model is applicable under relatively cloud-free, undisturbed synoptic conditions. The primary physical processes included in the model are:

Nocturnal Simulation:

- Transport by down-valley drainage flows.
- Plume channeling within the valley.
- Enhanced horizontal and vertical diffusion due to topography.
- Plume reflections off valley floor and sidewalls.
- Pollutant diffusion out the top of the valley.
- Dilution of the plume due to clean air inflow from tributaries.

Post-Sunrise Simulation During Temperature Inversion Breakup Period:

- Convective boundary layer growth.
- Plume subsidence in the valley inversion.
- Fumigation into growing convective boundary layers.
- Transport and diffusion in upslope flows over the sidewalls.

The inputs required are the valley physical characteristics, the source characteristics, the nighttime downvalley windspeed at the release height, temperature inversion characteristics at sunrise, and sensible heat flux as a function of time following sunrise.

Estimating drift of aerial sprays requires the treatment of additional processes beyond those currently addressed in VALMET. Additional key processes important for making drift estimates are: 1) time and spatially-varying releases; 2) nonsteady and nonhomogeneous along-valley winds and diffusivities; 3) cross-valley circulations and subsidence; and 4) interactions with above-ridgetop winds.

VALMET will be modified to incorporate these processes in a highly simplified fashion, with the modified version designed to operate through at least one diurnal cycle for a single valley. The basic approach for incorporating the key processes into VALMET is to solve a 1-D (along-valley) pesticide conservation equation for each of a number of "flowtubes" aligned along the valley, as illustrated in figure 7.

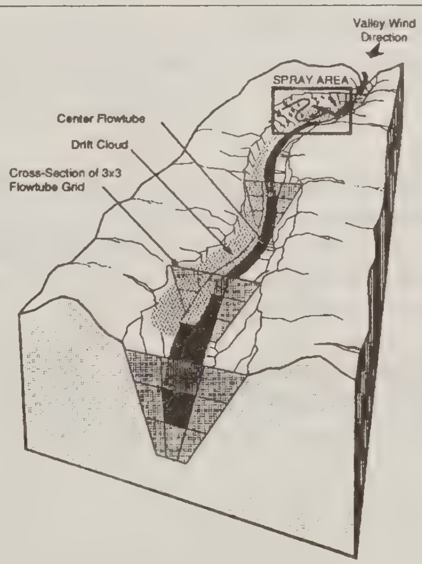

Figure 7.—Illustration of the flowtube concept for treating transport and diffusion from aerial spraying of pesticides in valleys. The central flowtube of nine sample flowtubes is shown.

The flowtube grid is generated by specifying the number of flowtubes in the cross-valley and vertical directions. A starting cross-section is divided into the desired number of layers in the vertical direction, and each layer is divided into the desired number of flowtubes in the cross-valley direction. The entire grid is generated using the conditions that the flowtubes are always horizontal in the cross-valley direction, conformal to the valley sidewalls in the vertical direction, and the ratio of the cross-sectional area of each flowtube to the total cross-sectional area of the valley is constant in the along-valley direction.

Interactions among flowtubes can occur and are handled through source/sink terms in each conservation equation. The pesticide conservation equation solved for each flowtube is:

$$\frac{\partial[A(x)C(x,t)]}{\partial t} + \frac{\partial[\dot{V}(x,t)C(x,t)]}{\partial x} + \Gamma_i(x,t) = 0 \quad (1)$$

where:

t is time,
x is the down-valley coordinate following the valley floor,
C is the pesticide concentration [ug/m^3],
A is the cross-sectional area of the flowtube [m^2],
$\dot{V}$ is along-valley air volume flow rate through the flowtube [m^3/s],

and the Γ_i are the pesticide source/sink terms for the flowtube [ug/s m].

The concentration is constant in the cross-valley and vertical directions in each flowtube, but can vary among flowtubes. The concentration can vary in the along-valley direction in each flowtube.

The first terms in Eqn. (1) is the rate of change of storage of pesticide in the control volume (A dx), and the second term is the along-valley advection of pesticide. The various source/sink terms in Eqn. (1) are illustrated in figure 8, and may include lateral and vertical turbulent diffusion, lateral and vertical advection, emission sources, deposition, and chemical transformations. Turbulent diffusion and advection will be treated in a highly simplified fashion. Advection can result from subsidence, cross-valley circulations, tributary flows, and/or interactions from aloft. Tributary flow, deposition, and chemistry source/sink terms will be added at a later date.

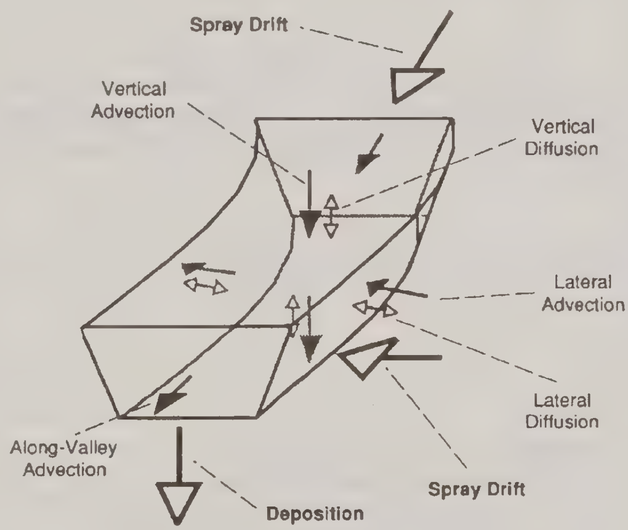

Figure 8.—Illustration of a valley flowtube control volume element showing the individual source/sink terms. Advection terms are indicated by the medium-size arrows on each of the faces of the control volume; diffusion terms are indicated by the four small double arrow terms (along-valley diffusion is neglected); other terms include deposition, emissions into the control volume (not shown), and chemical or physical transformations of the pesticide (not shown).

Figure 9 shows an example of the application of the flowtube approach on a valley cross section at a time corresponding to time, t_2 in figure 3.

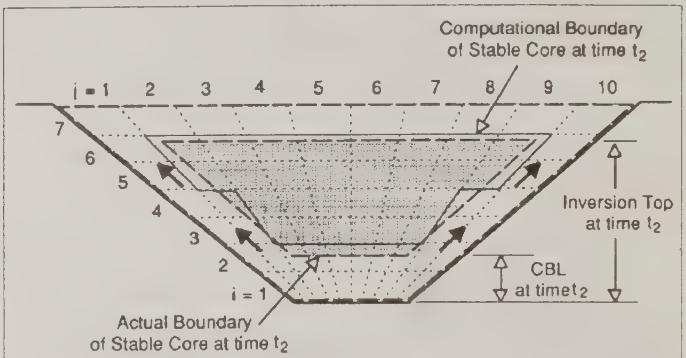

Figure 9.—Illustration of the computational domain on a valley cross section at a time corresponding to time t_2 in Figure 3. The stable core, CBL, and inversion top are shown within a 7 by 10 array of valley flowtubes.

In addition to conserving pesticide mass within the flowtubes, the model will also conserve total air mass, both for the along-valley flow in each flowtube and for the entire valley, using the air mass conservation equation:

$$\frac{\partial \dot{V}(x,t)}{\partial x} + \gamma_i(x,t) = 0 \qquad (2)$$

where:

$\dot{V}$ has been previously defined, and

γ_i are the air mass source/sink terms [m^3/s-m].

Nonrecirculating lateral flows are treated as source/sink terms in (2). Possible sources/sinks of air mass are from regional flow intrusions (e.g., subsidence) and tributary flows.

The additional inputs required by the modified VALMET are time-and-space dependent (if available) along-valley winds, lateral and vertical diffusivities, subsidence rates (optional), cross-valley circulation strengths (optional), and pesticide release characteristics (from AGDISP).

Outputs from the modified VALMET will include pesticide airborne concentration and deposition as a function of time and down-valley distance for each of the flowtubes.

Summary and Conclusions

The objective of this project was to develop a model to predict drift of aerial spray in mountainous terrain. The model is intended to be incorporated into the existing aerial spray models, FSCBG and AGDISP. An in-depth analysis of the current knowledge of mountain meteorology demonstrated that air movements in mountain valleys during the morning transition period are well enough understood to develop useful planning tools to improve aerial spraying. A systematic review of mesoscale meteorological models was made to select a model for adaptation. We concluded that a phenomenological model was needed because of the rapid changes in the convective boundary layer in the mountainous terrain. The model selected was VALMET. It is phenomenological, mesoscale, has good documentation, is operational, and uses computer resources compatible with AGDISP and FSCBG. The VALMET program was installed on a DOS-based personal computer. Enhancements and a plotting package developed for AGDISP were added to VALMET. Some software interfaces between AGDISP and VALMET have been completed, with interim documentation on these changes. Several additions will be made to VALMET to incorporate varying emissions and winds, cross-valley circulations, and subsidence. The equations for these additions are nearing completion and the software will be developed next. Long range plans include the testing of the AGDISP-VALMET modeling system with spray project data from complex terrain areas.

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